Network Models of Minority Opinion Spreading: Using Agent-Based Modeling to Study Possible Scenarios of Social Contagion

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Abstract

Although several models in the literature analyze the dynamics of opinion formation, less attention has been paid to explain how the structure of social networks and their contextual circumstances can influence the course of minority public opinions. This work aims to pose three basic questions: (1) how the structure of social networks can affect the spread of minority opinion, (2) how committed agents influence this process, and (3) how mass media action, as a contextual factor, can vary different agents' opinions and network composition. Agent-based modeling is used to create a network model of preferential attachment to explore how phenomena of minority opinion spreading can evolve under different simulated scenarios. This study shows that the success of minority opinions depends on network structure and composition and thus on external factors such as mass media action that can mediate the strength of these internal determinants. Although people tend to remain silent when they feel that their opinions are in the minority, our findings suggest that prevailing majority opinion may be promptly replaced by what was formerly minority opinion if core agents in the network structure and/or external sources support this view.

Keywords

minority opinions, social contagion, computational sociology, research methods, agent-based modeling

Introduction

The shaping of public opinion through processes of social interaction has been a subject of significant interest in such social sciences as sociology, political science, communication studies, or psychology and more recently in additional research fields such as physics, engineering, or computing. In fact, at present, the processes of opinion spreading and social contagion have acquired special relevance due to the spread of Internet and the proliferation of such online social media as Twitter, Facebook, or Youtube, platforms that are currently essential to explain, for instance, new rising social movements (e.g., Arab revolts, May 15th, Occupy Wall Street, etc.) or other contemporary global phenomena related to the use of these technologies (e.g., solidarity movements, global health, or ecology campaigns).

Although there are currently various models in sociophysical literature analyzing the dynamics of opinion formation (Axelrod, 1997; Deffuant, Neau, Amblard, & Weisbuch, 2000; Galam, 2002, 2003, 2012; Galam & Zucker, 2000; Galam, Chopard, Masselot, & Drozet, 1998; Hammond & Axelrod, 2006; Hegselmann & Krausse, 2002; Stauffer, 2003; Sznajd-Weron & Sznajd, 2000; Wang, Huang, & Sun, 2014; Weidlich, 2002), less attention has been dedicated to explain how the combination of the structure of social networks with their contextual circumstances (or external factor to the network that determines its performance) might affect the course of public opinion. Previous studies demonstrate that physical factors like network connectivity represent a crucial determinant of social contagion (Centola, 2009). In terms of complex contagions, the diffusion of opinions needs two basic prerequisites: (1) a single contact between nodes and (2) a certain predisposition to acquiring new information, either to fill a gap of knowledge (consciously or unconsciously) or to reinforce previous beliefs. However, while the diffusion of information across social networks, understood as a "simple communication process," only requires connectivity between nodes, the processes of opinion spreading require multiple reinforcing ties to survive (Centola, 2009). In real life, successfully extending a specific opinion (its triumph) depends on the connectivity between nodes and, obviously, on the social legitimacy of groups and their ideas in different normative contexts. In other words, the processes of opinion spreading are related to the social consensus between groups (Centola & Macy, 2007; Centola, Eguiluz, & Macy, 2007; Tessone, Toral, Amengual, Wio, & San Miguel, 2004). Opinions socially allowed, those prohibited or criticized, those successful or which have failed in their (conscious or unconscious) attempt to spread, all depend not only on network structures but also on community consensus between majority and minority groups, where the latter are generally silenced (Pentland, 2014).

In the realm of political science and mass communication studies, the spiral of silence theory—propounded by Elisabeth Noelle-Neumann (1974)—tries to explain why minority opinions remain silent when society threatens individuals with a fear of being isolated (Noelle-Neumann, 1974). The spiral of silence theory explains opinion dynamics in terms of assuming a dual climate of opinion: (1) opinions that are shaped through individuals' interactions with mass media (i.e., indirect observation of reality through the eye of the media) and (2) opinions that are related to our reference social groups (i.e., direct or first-hand observation of reality). In this theory, individuals are assumed to be active agents able to monitor the dual climate of opinion (mass media and public opinion) and to intuitively compute the prevalence of public opinion in a specific context in order to avoid being punished by society for holding a (possibly controversial) minority opinion (Noelle-Neumann, 1974, 1993). Taking into account these considerations, the spiral of silence theory points out that individuals will probably fall silent if they consider their opinions differ from the dominating ideas of the majority group, which are generally linked to mass media.

The reinforcement of the above-mentioned dynamics leads to the progressive emergence of the spiral of silence phenomenon. From this point of view, agents' individual reluctance to express their opinion at the micro level, simply based on intuitive perceptions of what everyone else thinks (or is expected to think), has important implications in explaining the emergence of complex social dynamics at macro level. Nevertheless, there are many debates and criticisms concerning this theory.

Different studies have found inconsistent results and methodological problems in articulating analysis at both the aggregate level (i.e., contextual variables) and the individual level (i.e., individual predictors related to agents' social behavior; Donsbach & Traugott, 2007; Glynn, Hayes, & Shanahan, 1997; Scheufle & Moy, 2000).

Taking into account these previous findings from social sciences and computational physics, this work aims to study the process of spreading minority opinion in four possible scenarios, giving response to three basic questions: (1) how the structure of social networks (i.e., network composition: types of nodes and number of edges) can affect the spread of minority opinion (''network physical structure'' effect), (2) how committed agents can influence in this process (''opinion loyalty'' effect), and (3) how mass media action, as a contextual (or external) factor, might vary agents' opinions and network composition (''media opinion'' effect; De Fleur & Ball-Rokeach, 1989; McQuail, 2000; Perse, 2001).

These specific objectives are based on the following hypotheses:

Hypothesis 1: Highly interconnected network structures might favor the processes of spreading minority opinion.

Hypothesis 2: Agents' commitment (AC) could mediate the strength of structural determinants in social networks.

Hypothesis 3: The combined effect of network structure and AC might be drastically affected by the presence of external mass media effects.

Method

Agent-Based Modeling Approach

In this study, agent-based modeling (ABM) is used to perform a network model to explore how phenomena regarding the spread of minority opinion can evolve under different simulated scenarios. ABM could be defined as a specific type of computational model aimed at simulating the behavior of autonomous agents and also their interactions under specific contextual conditions. Even though agents are generally identified as individual entities, they can also represent collective or aggregated units like organizations (e.g., hospitals, schools, etc.) or groups (e.g., medial consultation associated with a specific doctor, classes of students in a school, etc.; Squazzoni, Jager, & Edmonds, 2014).

ABM involves a broad approach that is grounded in multidisciplinary fields such as complexity science, game theory, computational sociology, and evolutionary programming, and whose objective is to study and assess the effects of individual actions of autonomous agents and their interactions on the system as a whole (Gilbert & Troitzsch, 2005). Probably, the main advantage of this methodology is not only the possibility of re-creating and predicting social behavior (despite the inherent difficulty associated with the study of human actions) but especially of understanding how small micro-actions can evolve into global macro-dynamics and thus the emergence of complex social phenomena.

For the present analysis, the simulation model will be based on a network of agents that has been developed to understand the conditions that guarantee processes of spreading minority opinion. The algorithm used in this simulation is the Barabási–Albert (BA) model (1999). This model has been chosen because scale-free networks are very common in natural and human-made systems, including, for example, the World Wide Web and networks in online social media. The BA model is an algorithm that generates random scale-free networks using a preferential ''attachment mechanism'' in which agents, step by step, prefer to join other agents who have many neighbors. This procedure leads to the emergence of highly connected clusters, while most agents in the network have very few connections.

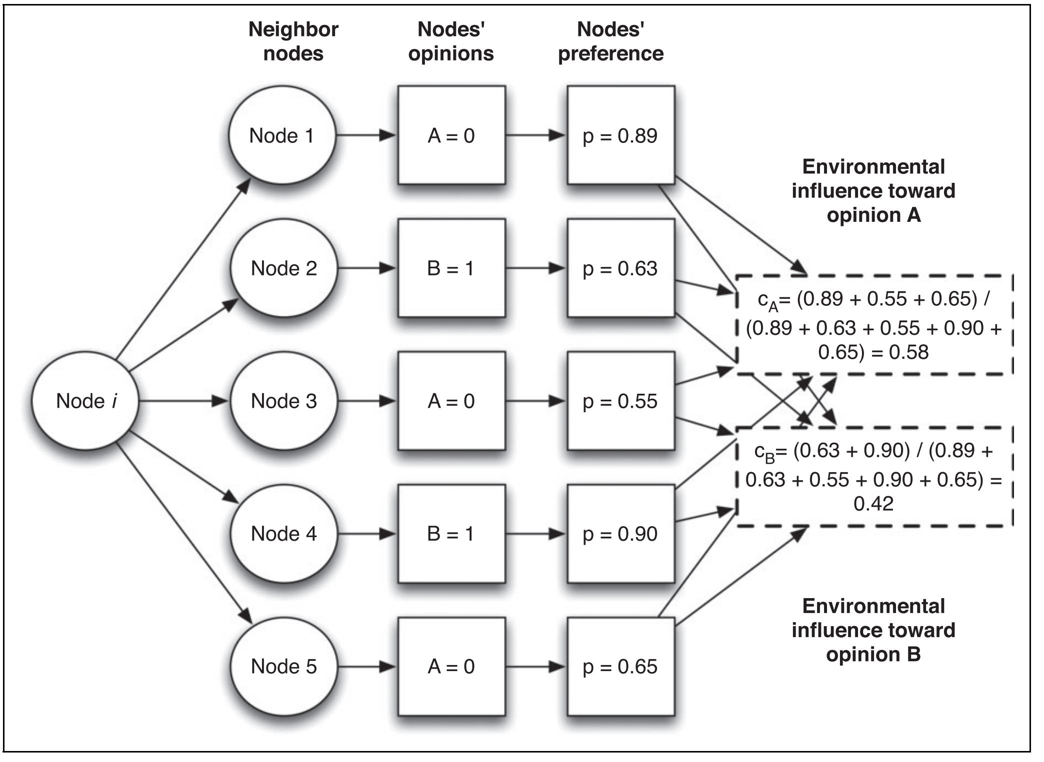

Figure 1. Example of the mechanism of environmental influence.

Basic Parameters

The model is initialized with a population of N interacting agents. In this model, agents can choose between two opposed opinions (A–B). For an easy interpretation, the model is set with $N = 1{,}000$ nodes, 10% of minority agents holding opinion B ($N = 100$ nodes) and 90% majority holding opinion A ($N = 900$ nodes). This initial sample size was considered relatively adequate to simulate the phenomena under study, without introducing much complexity in the final solutions. Again for simplicity only two opinions were considered. In this model, let $o_{j,i}$ be the opinion of agent j upon two possible choices i ($i = 0, 1$) and assume that p is a random variable, ranging from 0 to 1, which denotes the preference toward these alternatives. The environmental influence of A–B opinions, in this model denoted as c_i, could be mathematically expressed as:

$$c_i = \left(\sum_j o_{j,i} p_j\right) / \sum_j p_j. \tag{1}$$

For example, lets suppose we have a network with nodes in favor of A and B opinions. How can we compute the environmental influence that pushes the $node_i$ (or $agent_i$) to hold a certain opinion? Figure 1 shows a description of this process.

Simulated Scenarios

In addition, this model simulates four possible processes of minority opinion spreading based on different assumptions or potential scenarios (Table 1). In these scenarios, the preference toward a certain opinion is set according to different rules that are described on next sections.

Table 1. Simulated Scenarios Based on Opinions: Ideal Typologies, Possible Models, Micro-Mechanisms, and Examples.

Scenario: Opinion Type	Explanatory Model	Phenomenon under Study	Social Agreement	Explanation	Real Example
Scenario 1: trivial opinion	Random individual contagion	Conformity, based on initial lack of information	Easy consensus, because there is no previous knowledge or argumentation	You choose one of your neighbors randomly and adopt their opinions.	Conformity between virtual communities that can choose between different *unknown* alternatives (e.g., using Whatsapp, Telegram, or Line).
Scenario 2: reasonable (or argued) opinion	Learning (or reward)	Social choice, based on different known alternatives	Intermediate (or neutral), depends on the arguments	Your opinion might change over time, if your neighbors have arguments to change your opinion and you are not committed to your previous opinion.	Individuals that initially are free to decide, are progressively influenced (by other neighbors) to adopt a specific opinion (e.g., vote a right-wing candidate).
Scenario 3: controversial micro (peer group)	Preferential attachment	Group polarization, based on private social desirability bias	Probable dissension and silencing behavior	Your opinion depends on your neighbors' opinion. In this case, your decision to change your opinion depends on the percentage of neighbors.	Controversial opinion that is generally silenced, unless a certain percentage of neighbors sustain it (e.g., opinions on appropriate sexual behavior).
Scenario 4: controversial macro (public opinion)	Preferential attachment and selective exposure	Group polarization, based on public social desirability bias	Probable dissension and massive silencing behavior	Your opinion depends on your neighbors' opinion and also on media information. In this case, your opinion depends on a dual climate of opinion (peers + media opinions)	Controversial opinion at the macro level that might be silenced, unless a certain percentage of neighbors and media sources sustain it (e.g., vote a declared anti-immigration party).

Random model. The random model is based on the idea that, under certain circumstances, agents adopt (or are influenced by) the opinion of their neighbors in a random manner. In this computational model, agents choose one of their neighbors randomly and adopt the respective neighbor's opinion. Therefore, this could be defined as a model of "easy consensus" where agents, with no previous knowledge or preference, randomly decide to follow one opinion and discard another (i.e., preference is randomly set and does not depend on the percentage of neighbors holding a certain opinion). For example, this model could be possible in the case of conformity between communities that might choose between different unknown alternatives, and when the selection of alternatives does not imply important consequences. One example could be when some individuals decide to use a new mobile messaging app (e.g., Telegram) and discard other alternatives that present similar utilities (e.g., WhatsApp or Line).

Learning-based model. This model simulates a situation where agents listen to their neighbors' opinions, adding arguments for the selection of one concrete alternative, and update their probability of using one opinion (A) or the contrary (B). The algorithm is based on the progressive weighing of opinions they have heard by a preestablished α value (0.01), a process that progressively increases the preference toward a concrete alternative. That is, the more the agents heard one specific opinion, the more probability there existed of embracing that opinion. In the learning-based model, agents' opinions might change over time: if (1) their neighbors have arguments to change their initial opinion and (2) they are not committed to a previous opinion. For example, this could be the practical case where individuals who are initially free to decide are progressively influenced (by other nearby neighbors) to adopt a specific opinion that is repeatedly heard (e.g., you should vote for a right-wing candidate). The idea behind this process is that agents will probably follow the more widespread opinion in their context, the idea with greater probability of being heard.

Threshold model. In the threshold model, trying to study the silencing processes of public opinions, agents adopt one opinion if a certain percentage of their neighbors have already adopted this opinion. In this scenario, agents' opinions change depending on the proportion of neighbors that support the minority/majority opinion. That is, an individual will modify his or her initial opinion (A) only if there is a certain fraction of neighbors already holding the opposing opinion (B). In this case, the process of opinion spreading is mainly affected by the percentage of others' opinions or, in other words, the external "opinion climate" in the social networks. In this model, agents retain the new opinion one they have changed to (i.e., cannot go back to the previous opinion) if the percentage reaches the previously defined threshold values. For instance, this could be the case for a controversial opinion that is generally silenced (Bartha & Wolszczak-Derlacz, 2009), unless a certain percentage of neighbors sustain it. Among many other examples, we could include public opinions about appropriate sexual behavior, ideas on drug consumption, and so on. That is, opinions that are generally silenced in public but that could be expressed in private environments.

Media effects model. In the fourth model, simulating the spiral-of-silence effect produced by a dual climate of opinion, agents adopt one opinion if a certain percentage of their neighbors and (observed or heard) mass media are already of this opinion. In this model, agents' opinion change depended on both the proportion of neighbors supporting the minority/majority opinion and the proportion of mass media sources in their context with opinion A or B. Therefore, individuals will change their initial opinions only if there is a fraction of neighbors and (observed) media sources holding another opinion. For simplicity, this model included 100 media sources that are randomly distributed in the lattice, and agents visibility reached to a maximum of two patches (i.e., spaces in the simulated environment). These values were assumed according to the size of the network and the distance between nodes, so that at least a minimum percentage of nodes could be influenced by these external sources of information. In the model, trying to simulate a society of limited media influence (McQuail,

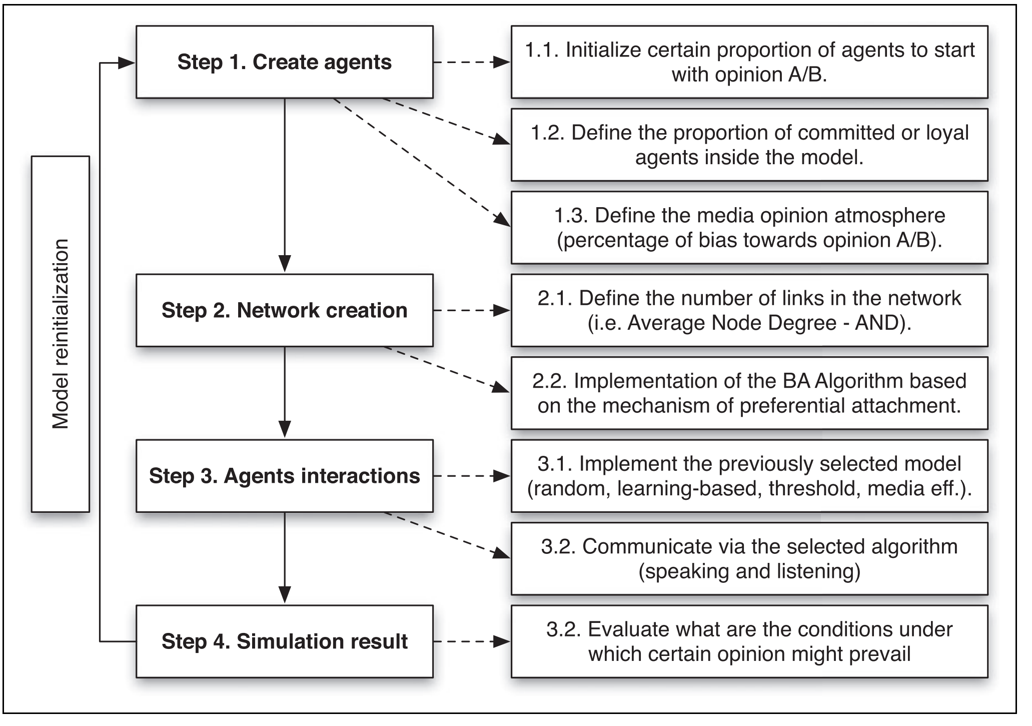

Figure 2. Model implementation.

2000), the media effect was randomly set in a range of 10–30% of agents supporting minority opinion.

The media effects models reproduce the practical case of controversial opinion at the macro level (or the level of mass communication) that could be silenced unless a certain percentage of neighbors and media sources sustain it (e.g., positive opinions toward declared anti-immigration parties, racist thoughts regarding immigration, sexist ideas, etc.).

Additional parameters. Once the four simulated scenarios have been defined, other parameters such as average node degree (AND) and AC were added to the model in order to introduce more complexity and practicality to the initial conditions (Figure 1). AND could be defined as the average degree of connectivity between the nodes in the network. The AND is a measure of how many edges (or links) are in a network compared to the number of nodes (or vertices). In addition, following previous studies (Biswas & Sen, 2009; Mobilia, Petersen, & Redner, 2007), committed agents were included in the model. Committed agents could be defined as agents loyal toward minority–majority opinions that do not change their initial state (A or B opinions). Committed agents maintain their opinion when they hear majority and minority opinions. In other words, these "inflexible" agents maintain their initial ideas against external influences ($p_i = 1$) and are likely to produce a magnetization (or reinforcement) effect on their nearest neighbors. A description of the implementation process is depicted step by step in Figure 2.

Results

The implementation of the ABM (Table 2) indicates that the success of minority opinions does not only depend on network structure and composition but especially depend on external factors such as

Table 2. Model and Initialization Conditions.

AB Models	Initialization Conditions	Average Node Degree	Committed Agents	Threshold (% neighbors)	Media effects (% bias B)
Random	1,000 Nodes; 10% opinion B, 90% A	1–5–10	No	No	No
	1,000 Nodes; 10% opinion B, 90% A	1–5–10	10% of Bs	No	No
Learning based	1,000 Nodes; 10% opinion B, 90% A	1–5–10	No	No	No
	1,000 Nodes; 10% opinion B, 90% A	1–5–10	10% of Bs	No	No
Threshold	1,000 Nodes; 10% opinion B, 90% A	1–5–10	No	30%	No
	1,000 Nodes; 10% opinion B, 90% A	1–5–10	10% of Bs	30%	No
Media effect	Equal conditions + 100 media sources	1–5–10	No	30%	100 media, 10–30% (VSBT = 2)
	Equal conditions + 100 media sources	1–5–10	10% of Bs	30%	100 media, 10–30% (VSBT = 2)

Note. AB model = agent-based model; VSBT = visibility.

mass media information or AC that can mediate the strength of these structural determinants. In spite of the fact that people tend to remain silent when they feel that their opinions are in the minority, our findings suggest that prevailing majority opinion (A) may be replaced by formerly minority opinion (B) depending on various conditions.

Figure 3 shows that minority opinions (B; 10%) are more probable to win over the majority opinion (A; 90%) if (1) a certain proportion of loyal or committed agents in the network structure support the minority opinion (at least 10% committed), (2) there is a high degree of connectivity between neighbors (i.e., nodes live in a small world), and/or (3) when external sources (i.e., mass media information) provide greater external support to a minority group (10–30% media sources hold opinion B).

In order to compare the four models, Figure 3 shows six possible initializations in the scenarios of random, learning-based, threshold and media effects: (1) AND equal 1 without committed agents, (2) AND equal 5 without committed agents, (3) AND equal 10 without committed agents, (4) AND equal 1 with 10% committed agents for B, (5) AND equal 5 with 10% committed agents for B, and (6) AND equal 10 with 10% committed agents for B.

Scenario 1: Individual Random Contagion

Committed agents have proved to be critical in the model of *individual random contagion*. Although it is highly probable that minority opinion (10% agents with opinion B) will lose out, this probability could easily be reversed if a minimum proportion of agents are loyal to opinion B. In addition, a higher AND between nodes increases exponentially the speed of opinion contagion in both situations (i.e., minority opinion wins or loses). That is, an increase in the number of links or connections between agents multiplies the channels for social contagion of both majority and minority opinions. As a result, in the context of an individual random model, the combination of a mid-high network connectivity (AND = 3 or higher) and a minimum percentage of committed agents gives rise to a favorable scenario for the success of minority opinions and, in parallel, increases exponentially the speed of social contagion.

Scenario 2: Learning-Based Contagion

The *learning-based model* is the least favorable for processes of minority opinion spreading. In fact, the learning-based model greatly reduces the probability of success for minority opinion since this model is based on a summative criterion of opinions that have been heard. In other words, we could say that the majority group has a greater advantage in expressing their opinions and also being heard in the simulated world (especially if individuals composing this group are highly interconnected). Although this model does not confer any rationality to the agents in the simulation, the learning-based algorithm progressively increases the number of arguments for the selection of a specific alternative (opinion A or B) with respect to opinions heard. Thus, when agents are in the minority pole, they are less likely to spread their opinion, even if network connectivity is high and there are committed agents that support the minority opinion. In fact, a higher connectivity favors agents in the majority group since they have higher opportunities to transmit their opinion. For this reason, it could be stated that a knowledge-based (or rational) scenario does not guarantee the success of minority opinions. In other words, minority opinions will probably be silenced in social contexts where opinions are essentially grounded in reasonable opinions and learning-based processes based on a cumulative criterion of listened opinion.

Scenario 3: Threshold-Based Contagion

The *threshold model* is based on assuming the existence of controversial opinions that could be silenced depending on the percentage of neighbors holding the same opinion. Taking this consideration into account, it is easy to understand that, in the ABM simulation, the minority opinion contagion based on the threshold model generally wins when the AND is mid-high (AND = 3–5). In this model, agents embrace one opinion if a certain proportion of their neighbors are already using this opinion, so when the agents live in a small world (i.e., a network with a high degree of connectivity between nodes, independently of the distances between ties), it is highly likely for them to locate other neighbors holding minority opinions. In this scenario, minority opinion can easily become the majority. However, if connectivity is too high (AND > 5), this advantage may progressively decrease. In other words, hyper-connected networks also increase the probabilities for listening opposed opinions that are susceptible to modify the previously adopted ideas.

On the other hand, the inclusion of committed agents seems to reinforce marginally this tendency. That is, opinion loyalty of certain committed agents increases the possibilities of locating additional B opinions that could change A opinions, but the effect is very small to be really significant in the model.

Scenario 4: Media Effect Contagion

Finally, the media effects model is based on the spiral-of-silence assumption of the existence of a dual climate of opinion to publically express controversial or non ethical ideas (e.g., anti-immigration opinions, racist thoughts, sexist ideas, etc.). This model might be considered an extension of the threshold model since agents adopt one opinion if a certain percentage of their neighbors and (observed or heard) mass media sources are already holding a specific opinion. Figure 4 shows in detail the six possible initializations in the scenarios of threshold and media effects.

As can be observed, the inclusion of the media effect increases the bias of the initial model. In this case, agents listen to both neighbors and external media information that randomly appear in the lattice (if these sources are available). Media sources are defined in the model as motionless cellular automata that are situated in a second layer (i.e., as an environmental characteristic in the simulation). Media sources are more or less visible for the agents in the simulation depending on the agents' interest in listening to new information. The initial model with media effects included 100 media sources and agents in the world with visibility equal 2 (VSBT = two patches [or spaces in the lattice]). That is, agents are supposed to observe only adjacent media sources but not those that are positioned too distant.

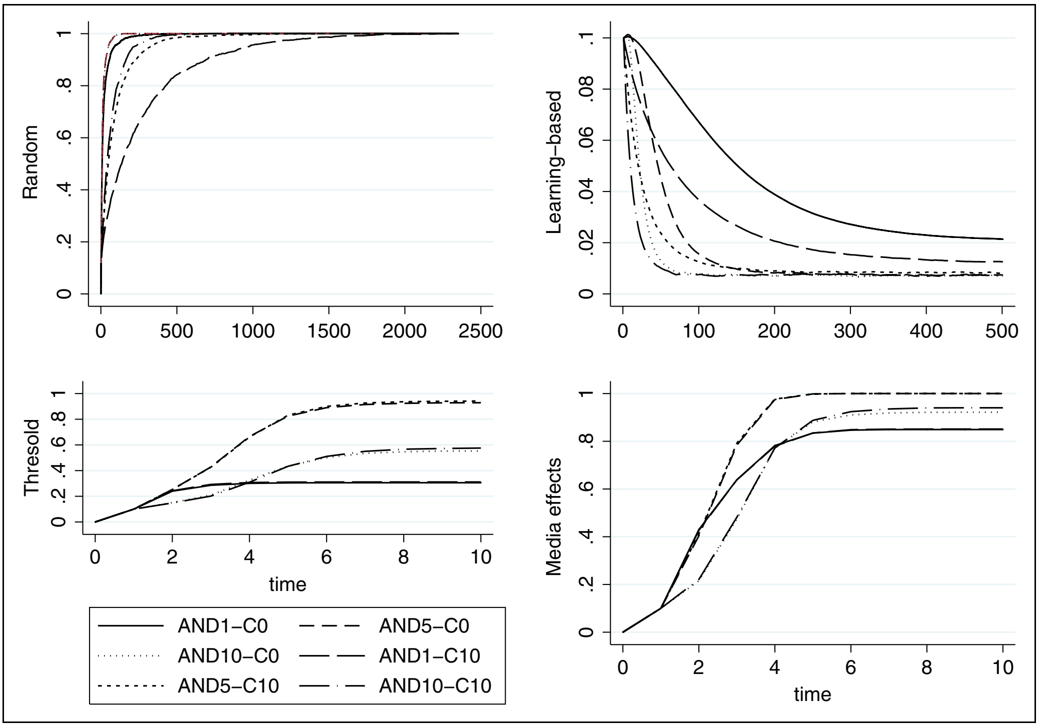

Figure 3. Mean results of the four ABM. Results after 1,000 simulations. ABM = agent-based modeling.

The inclusion of media effects (10–30% for B) significantly increases the bias toward minority opinions and varies the structural effect of the network and the position of (committed or noncommitted) agents. These combined models demonstrate that the initial relevance of the network structure could be drastically reduced or even reinforced with the presence of other communication channels. In addition, as observed in Figure 4, the presence of a minimum proportion of committed agents (10% of agents holding minority opinion B) does not produce important variations in the models. In fact, the inclusion of committed agents does not essentially vary the slope of the lines for these simulated models. On the contrary, certain increase in AND produces important effects in the success of the process of minority opinion spreading. That is the reason why we can confirm that the general success of both models is closely related to the level of connectivity between the nodes in the network, whereas the inclusion of committed agents does not produce important variations in the process of opinion contagion.

Figure 5 compares the global results for the threshold and media effects models. This figure demonstrates that the presence of external sources of (media) information could produce important changes in models' outcomes, independently of the presence of committed agents and the degree of connectivity between agents.

Discussion

Results and Methodological Approach

As hypothesized, there exist networks that might favor the processes of spreading minority opinion. First, highly interconnected network structures might favor the processes of spreading minority opinion but especially in processes of individual random contagion. In fact, AND might reverse its

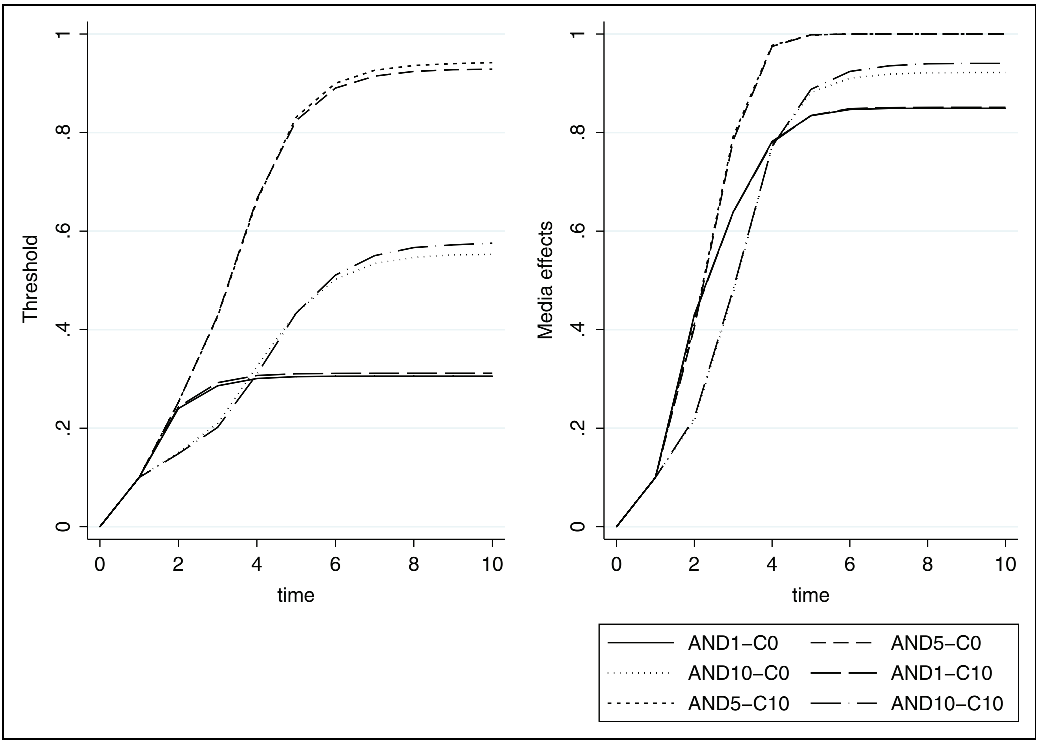

Figure 4. Average node degree and committed agents (10%; B) effects on threshold and media effect models (mean results after 1,000 simulations).

positive effect under specific circumstances (e.g., learning-based scenarios or highly interconnected threshold models). Second, AC could mediate the strength of structural determinants in social networks, but the proportion of committed agents should be higher than 10% (of minority opinion) to produce significant effects. Finally, the combined effect of network structure (based in AND) and AC might be drastically affected by the presence of external mass media effects.

The present work shows how different network models that are theoretically based on different opinion types could produce extremely different results. Individual random-contagion models could be based on a conformity mechanism due to the lack of initial information and predisposition toward certain opinions, while learning or threshold models imply social choice based on different known alternatives and also on neighbors' opinions and expectations for what should be considered appropriate public behavior. Finally, the inclusion of media effects introduces external information into the artificial world and produces a simulation that could initially be more realistic and also more complex to predict, especially because this effect can modify the impact of global connectivity in the network. In other words, it could be said that the positive effect of network connectivity could be reduced if there existed external communication channels to support opposite majority opinions. Thereafter, the external climate of opinion is a contextual (or second level) mediator of the effect of individual predictors of minority-opinion spreading processes (e.g., number of neighbors in my social networks, social affinities with my peers, degree of commitment or loyalty).

Of course, it is known that mass media information can modify our opinion, attitudes, and social behavior, especially under certain contextual circumstances where social agents have no firsthand information to help choose their alternatives (Ball-Rokeach, 1998; De Fleur & Ball-Rokeach, 1993). As a result, when agents do not obtain information from their network and they have to look

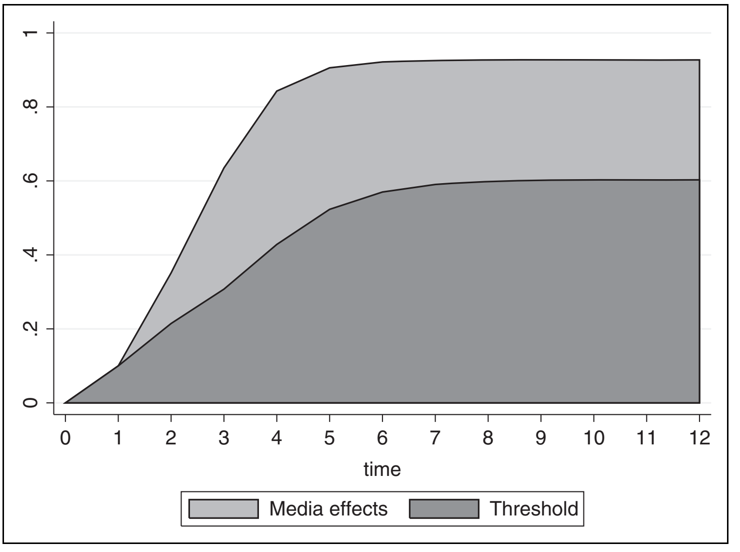

Figure 5. Mean results for threshold and media effects models (1,000 simulations).

for additional data in external media sources, media effects could become stronger in this situation. Clearly, the outcomes of the processes that spread minority opinion are hardly predictable when agents receive changing information from both these channels (i.e., social networks and mass media sources). However, in order to better understand these complex processes, our simulation could be adjusted if, under specific contexts, we assume that certain communication channels are more prevalent or show more predictive power in the global result.

Compared with previous approaches that analyze isolated models of minority opinion spreading, the present article (a) offers the possibility of finding new or alternative hypotheses about the processes of opinion spreading based on combined and dynamic scenarios that are hard to achieve through conventional purely quantitative or qualitative methodologies, (b) shows that these combined models give researchers clear information in a controlled and artificial environment about the circumstances needed for minority opinions to win in a hostile context, and (c) offers essential information for policy makers to understand how their consciousness and/or educational campaigns (e.g., related to the promotion of health, ecological behavior, responsive use of public resources, etc.) could be more effective and efficient.

In fact, the theoretical knowledge obtained from these computational models could be combined with evidences from survey data in order to design more realistic simulations. For instance, in the field of health care, we could use previous knowledge (and existing data) on opinions or attitudes toward vaccination to study the structural and/or environmental reasons why certain behaviors occur and propagate in contemporary societies (e.g., parents who choose not to vaccinate their children). Therefore, these calibrated theoretical models describing different processes of minority opinion spreading, in combination with real data, might help us to understand how minority ideas, rumors, and misinformation may be propagated through mechanisms of social contagion. Consequently, these simulated models could contribute not only to the theoretical work of academic researchers but also to the practical design and implementation of an evidence-based policy through the combination of real data and expert knowledge.

In addition, the results of the present model for the study of minority opinion spreading could be relevant to understand the communication process involved in forming public opinion, social contagion dynamics, and the emergence of collective behavior in complex social systems. The model may also apply to the study of rumor propagation through social networks and opinion silencing processes.

Limitations and Future Orientation

This basic and limited model, with two competing opinions and four possible scenarios, has been performed to study the fundamental conditions for minority opinion propagation in small-world and scale-free networks, but future models should include additional opinions as well as inoculation effects (i.e., resistance to persuasion) that could hinder the process of social contagion. In order to introduce more realism into the final model, future works should introduce multiple opinions into the simulation, different levels of commitment or loyalty in agents, use real-world networks (e.g., obtained from social media such as Twitter or Facebook), study clustering effects, and the emergence of social communities. Obviously, taking into account the complexity of these simulated models, these are the next steps that should be addressed from independent research objectives because simultaneously simulating all these real-world phenomena might be so complex and fuzzy that we cannot understand the final outcome.

On the other hand, although the present study is based on the BA model that simulates random scale-free networks using a "preferential attachment" mechanism, future studies should consider other network types depending on the objectives of analysis. In this case, the mechanism of the BA model with preferential attachment was used because the objective of our simulation was aimed at simulating the spreading opinion processes through social networks in the real world. However, other studies could be focused on analyzing other network types (e.g., random networks) depending on which questions need to be answered. In addition, we could increase variability of the simulated models by using Monte Carlo simulations (Stauffer, 2003).

Taking into account the difficulties to study the complex collective dynamics of opinion formation under classic methodological approaches based on qualitative data, observational techniques, and survey methods in social sciences, the future success of the present work will depend on the use innovative and multidisciplinary approaches that combine real data extracted from online social networks and evidence-based knowledge from field and experimental methods. Therefore, the combination of different methodological approaches and the usage of real data from different sources (online social networks, media information, and survey methods) could contribute to the measurement and validation of specific processes of social contagion. Thus, the combination of theoretical knowledge, methods, and data from different research fields should contribute to fill the gaps of every discipline but also could provide radically new explanations and counterintuitive arguments that hardly could be discovered from unique research fields.

Conclusion

This study based on ABM methodology shows that the success of minority opinions depends on network structure and composition and especially on external factors such as mass media information that can mediate the strength of structural determinants in opinion spreading. This analysis indicates that although people tend to remain silent when they feel that they sustain minority opinions, prevailing majority opinion may be easily replaced by what was formerly minority opinion in specific scenarios. As literature on the collective formation and spread of public opinion shows, it is highly probable that the minority could win the game if (1) core agents in the network structure sustain and spread minority opinion, (2) there exists a high connectivity between the nodes in the network. However, as the present study indicates, it also could occur when (3) external media sources support this view, and especially (4) under combined situations that increase the general complexity of these processes and the difficulties to predict final outcomes. Combined circumstances enable the configuration of scenarios that, under certain circumstances, might be more or less favorable for the social contagion of minority opinions.

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Declaration of Conflicting Interests

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References

Axelrod, R. (1997). The dissemination of culture—A model with local convergence and global polarization. *Journal of Conflict Resolution*, *41*, 203–226.

Ball-Rokeach, S. (1998). A theory of media power and a theory of media use: Different stories, questions, and ways of thinking. *Mass Communication & Society*, *1*, 5–40.

Barabási, A., & Albert, R. (1999). Emergence of scaling in random networks. *Science*, *286*, 509–512.

Bartha, E., & Wolszczak-Derlacz, J. (2009). The power of silence? Opinion contagion and the surprise of the polish 2005 parliamentary and presidential elections. *Polish Sociological Review*, *165*, 123–138.

Biswas, S., & Sen, P. (2009). Model of binary opinion dynamics: Coarsening and effect of disorder. *Physical Review E*, *80*, 027101.

Centola, D. (2009). Failure in complex social networks. *Journal of Mathematical Sociology*, *33*, 64–68.

Centola, D., Eguiluz, V., & Macy, M. (2007). Cascade dynamics of complex propagation. *Physica A*, *374*, 449–456.

Centola, D., & Macy, M. (2007). Complex contagions and weakness of long ties. *American Journal of Sociology*, *113*, 702–734.

De Fleur, M., & Ball-Rokeach, S. (1993). *Fundamentals of human communication*. San Francisco, CA: Mayfield Publishing Company.

De Fleur, M. L., & Ball-Rokeach, S. (1989). *Theories of mass communication* (5th ed.). White Plains, NY: Longman.

Deffuant, G., Neau, D., Amblard, F., & Weisbuch, G. (2000). Mixing beliefs among interacting agents. *Complex Systems*, *3*, 87.

Donsbach, W., & Traugott, M. (2007). *The SAGE handbook of public opinion research*. Thousand Oaks, CA: Sage Publications Ltd.

Galam, S. (2002). Minority opinion spreading in random geometry. *European Physical Journal B*, *25*, 403–406.

Galam, S. (2003). Modelling rumors: The no plane Pentagon French hoax case. *Physica A*, *320*, 571.

Galam, S. (2012). *Sociophysics: A physicist's modeling of psycho-political phenomena*. Cambridge, England: Cambridge University Press.

Galam, S., Chopard, B., Masselot, A., & Droz, M. (1998). Competing spices dynamics: Qualitative advantage versus geography. *European Physical Journal B*, *4*, 529.

Galam, S., & Zucker, J. D. (2000). From individual choice to group decision-making. *Physica A*, *287*, 644.

Gilbert, N., & Troitzsch, K. (2005). *Simulation for the social scientist*. Milton Keynes, England: Open University Press.

Glynn, C., Hayes, A., & Shanahan, J. (1997). Perceived support for one's opinions and willingness to speak out: A meta-analysis of survey studies on the spiral of silence. *Public Opinion Quarterly*, *61*, 452.

Hammond, R. A., & Axelrod, R. (2006). The evolution of ethnocentrism. *Journal of Conflict Resolution*, *50*, 926–936.

Hegselmann, R., & Krausse, U. (2002). Opinion dynamics and bounded confidence: Models, analysis and simulation. *Journal of Artificial Societies and Social Simulation*, *5*, 3.

McQuail, D. (2000). *Mass communication theory* (4th ed.). London, England: Sage.

Mobilia, M., Petersen, A., & Redner, S. (2007). On the role of zealotry in the voter model. *Journal of Statistical Mechanics*, *2007*, P08029.

Noelle-Neumann, E. (1974). The spiral of silence: A theory of public opinion. *Journal of Communication*, *24*, 43–51.

Noelle-Neumann, E. (1993). *The spiral of silence: Public opinion-our social skin* (2nd ed.). Chicago, IL: University of Chicago Press.

Pentland, A. (2014). *Social physics: How good ideas spread—The lessons from a new science*. New York, NY: Penguin Press.

Perse, E. M. (2001). *Media effects and society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Scheufle, D., & Moy, P. (2000). Twenty-five years of the spiral of silence: A conceptual review and empirical outlook. *International Journal of Public Opinion Research*, *12*, 3.

Stauffer, D. (2003). "Sociophysics Simulations ", Computing in Science and Engineering 5(3), pp. 71–75; "How to Convince Others? Monte Carlo Simulations of the Sznajd Model", in AIP Conference Proceedings, *The Monte Carlo Method on the Physical Sciences: Celebrating the 50th Anniversary of the Metropolis Algorithm*, edited by Gubernatis, J. E., 690, pp. 147–155 = cond-mat/0307133.

Squazzoni, F., Jager, W., & Edmonds, B. (2014). Social simulation in the social sciences: A brief overview. *Social Science Computer Review*, *32*, 279–294.

Sznajd-Weron, K., & Sznajd, J. (2000). Opinion evolution in closed community. *International Journal of Modern Physics C*, *11*, 1157.

Tessone, C. J., Toral, R., Amengual, P., Wio, H. S., & San Miguel, M. (2004). Neighborhood models of minority opinion spreading. *The European Physical Journal B*, *39*, 535–544.

Wang, S. W., Huang, C. Y., & Sun, C. T. (2014). Modeling self-perception agents in an opinion dynamics propagation society. *Simulation*, *90*, 238–248.

Weidlich, W. (2002). *Sociodynamics—A systematic approach to mathematical modeling in social sciences*. London, England: Taylor & Francis.

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